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ALGORITHMS FOR CALCULATING THE ORIENTATION OF THE PROGNOZ ARTIFICAL EARTH SATELLITES

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16. Abstract

Algorithms for calculating the orientation of the Prognoz series artificial earth satellites are presented. Several different coordinate systems, including the Koenig coordinate system, are introduced and transition matrices from one coordinate system to another are discussed.

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ALGORITHMS FOR CALCULATING THE ORIENTATION OF THE PROGNOZ ARTIFICIAL EARTH SATELLITES

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I. Preliminary Remarks

We introduce into consideration the following coordinate systems: /3*

No. 1. An absolute geocentric, equatorial coordinate system. The axis $\vec{i}$ is directed to the point of spring, the axis $\vec{k}$, along the Earth's rotation axis, the axis $\vec{j}$ completes the system in clockwise direction. In all the following coordinate systems the origin coincides with the center of mass of the satellite.

No. 2. The Koenig coordinate system with axes $\vec{i}$, $\vec{j}$, $\vec{k}$ parallel to the axes of the absolute system.

No. 3. A bound coordinate system with axes $\vec{\xi}_1$, $\vec{\xi}_2$, and $\vec{\xi}_3$ directed along the main central inertial axes of the satellite.

No. 4. A coordinate system bound with the vector of the moment of momentum $\bar{l}$ of the rotation of the satellite in the Koenig coordinate system such that the axis $O\vec{L}$ is directed along $\vec{L}$, the axis $O\vec{L}$, lies in the plane OLK orthogonal to $O\vec{L}$ and forms an obtuse angle with $O\vec{K}$; the axis $O\vec{L}_2$ completes the system in clockwise direction.

No. 5. A constructed (base) coordinate system.

We will also consider the following matrices:

1. Matrix A -- a transition matrix from the Koenig coordinate system (or from the absolute coordinate system) to the constructed system.

2. Matrix B -- a transition matrix from the bound coordinate system to the constructed system.

3. Matrix C -- a transition matrix from the coordinate system bound with $\vec{L}$ to the bound coordinate system.

*Numbers in the margin indicate pagination in the foreign text.

4. Matrix D -- a transition matrix from the Koenig coordinate system (or from the absolute coordinate system) to the coordinate system bound with the vector $\delta \vec{L}$.

The matrix B is a function of the constructed characteristics of the object and for the given satellite is a constant.

The matrix C is a function of the position of the vector of the moment of momentum $\vec{L}$ in absolute space and is constant for the considered interval of processing the measurements. /4

II. The Calculation Algorithm

For interpreting the readings of the scientific equipment set up onboard the satellite it is necessary to calculate the angles between the directions of the devices given in the constructed (base) coordinate system, and the directions characterizing the astronomical or geophysical objects understood in the absolute coordinate system. The calculation of the indicated angles at a certain moment in time is supplied by a calculation at this moment of the transition matrix from the absolute coordinate system to the constructed system, i.e., matrix A.

These relations are valid:

$$A = B \cdot C \cdot D \;; \tag{1}$$

$$D = \begin{Vmatrix} \cos\sigma \cdot \cos\rho & \sin\sigma \cdot \cos\rho & -\sin\rho \\ -\sin\sigma & \cos\sigma & 0 \\ \cos\sigma \cdot \sin\rho & \sin\sigma \cdot \sin\rho & \cos\rho \end{Vmatrix} \;; \tag{2}$$

$$C = \begin{Vmatrix} \cos\varphi \cdot \cos\psi - \sin\varphi \sin\psi \cos\vartheta ; & \cos\varphi \sin\psi + \sin\varphi \cos\psi \cos\vartheta ; & \sin\varphi \sin\vartheta \\ \sin\varphi \cos\psi - \cos\varphi \sin\psi \cos\vartheta ; & -\sin\varphi \sin\psi + \cos\varphi \cos\psi \cos\vartheta ; & \cos\varphi \sin\vartheta \\ \sin\vartheta \cdot \sin\psi ; & -\sin\vartheta \cos\psi ; & \cos\vartheta \end{Vmatrix} \tag{3}$$

The Euler angles φ, ψ, and ϑ are determined at a given moment in time t by means of numerical integration of the differential equations of motion:

$$\dot{\varphi} = \delta \mu_3 \cdot L \cdot \cos\vartheta \left(1 - \frac{\mu_1}{\mu_3}\sin^2\varphi - \frac{\mu_2}{\mu_3}\cos^2\varphi\right) ; \tag{4}$$

$$\dot{\psi} = \delta \mu_3 L \left(\frac{\mu_1}{\mu_3}\sin^2\varphi + \frac{\mu_2}{\mu_3}\cos^2\varphi\right) ; \tag{5}$$

$$\dot{\vartheta} = \delta \mu_3 L \left(\frac{\mu_1}{\mu_3} - \frac{\mu_2}{\mu_3}\right)\sin\vartheta \sin\varphi \cos\varphi . \tag{6}$$

The parameters L, ρ, and σ, determining the magnitude /5
and direction of the vector of the moment of momentum in the absolute coordinate system, are assumed to be constant in the considered time interval of processing the reference data. The magnitudes μ_1/μ_3 and μ_2/μ_3, being relations of the main central moments of inertia of the satellite, characterize its dynamic properties and, as in matrix B, are constant for the given object.

The differential equations (4), (5), and (6) are integrated by the Adams method of the fourth degree with an automatic selection of the interval for a given accuracy of integration ε , is the scale factor.

If the position of some device understood in the constructed (base) coordinate system is given by the vector $\vec{l}$ and, in the absolute coordinate system, the direction, for example, to the sun, given by the vector $\vec{s}$, is calculated, then the angle α_{se} between the device and the direction to the sun is calculated according to the formula.

$$\alpha_{se} = \arccos(\bar{e}_c, A\bar{s}) \tag{7}$$

III. Initial Data.

As the initial data for calculating the orientation parameters at a given time t in the interval $[t_o, t_f]$ there are: t_o -- the initial time of the processing interval (hours, minutes); t_f -- the final time of the processing interval (hours, minutes); $\mu^3 L$ -- a five-digit number (units, tenths, hundredths, thousandths, ten-thousandths radian/sec); ρ, σ, φ, ψ, ϑ -- four-digit numbers (units, tenths, hundredths, thousandths of radians). The indicated magnitudes were defined for each interval of processing. /6

The matrix B, the parameters μ_1/μ_3, μ_2/μ_3, δ, and ε were defined for the given satellite as a whole.

IV. Results of Reference Error

1. Values of Initial Data:

t_1	=	1352 (13 hrs 52 min)
t_f	=	1402 (14 hrs 02 min)
$\mu^3 L$	=	98834 (9.8834 rad/sec)
ρ	=	1665 (1.665 rad)
σ	=	5882 (5.882 rad)
φ	=	4730 (4.730 rad)
ψ	=	1117 (1.117 rad)
ϑ	=	1588 (1.588 rad)

2. Values of Constant Parameters:

$$\frac{\mu_1}{\mu_3} = 0.518252$$

$$\frac{\mu_2}{\mu_3} = 0.747217$$

$$\delta = 10^{-2}$$

$$\varepsilon = 10^{-5}$$

$$B = \begin{Vmatrix} 0.999802 & -0.009308 & 0.017612 \\ 0.178680 & 0.808580 & -0.588114 \\ -0.008766 & 0.588312 & 0.808586 \end{Vmatrix}$$

3. Results of Reference Error at a given t time:

t	=	14 hrs 01 min 51.2 sec
φ	=	4.71422
ψ	=	31.4069
ϑ	=	1.59213

$$C = \begin{Vmatrix} 0.002025 & 0.021315 & -0.999771 \\ 0.999957 & -0.009105 & 0.001831 \\ -0.009064 & -0.999731 & -0.021333 \end{Vmatrix}$$ /7

$$D = \begin{Vmatrix} -0.086627 & 0.036771 & -0.995562 \\ 0.390731 & 0.920505 & 0 \\ 0.916420 & -0.388997 & -0.094108 \end{Vmatrix}$$

$$\bar{\ell}_c = \begin{cases} \ell_x = 0.128585 \\ \ell_y = -0.695103 \\ \ell_z = -0.707317 \end{cases}$$

$$\bar{S} = \begin{cases} -0.928800 \\ 0.339981 \\ 0.147457 \end{cases}$$

$$\alpha_{s\ell} = 1.51117_{\text{rad}}$$

An alternate variant of the algorithm is presented below.

The following parameters constitute the initial data /8 for the operation of the algorithm for determining the orientation of the satellite:

t_o -- initial Moscow time, sec;

t_f -- final Moscow time, sec;

c -- projection of a unit directional vector from the satellite to the Earth's center

d -- projection of a unit directional vector from the satellite to the center of the sun.

The coordinate system is geocentric equatorial with axis x directed to the vernal equinox point.

The parameters cited below of the constant on the interval of time

$[t_0, t_k]$: A_1, A_2, A_3, A_4, A_5, B_1, B_2, B_3, B_4, B_5 -- The coefficients for the trigonometric functions in an approximation of the laws of change of the angles α and β ω_1, ω_2, ω_3 are the phase frequencies; D_1, D_2, D_3, D_4, D_5,

F_1, F_2, F_3, F_4, F_5, are the coefficients for approximating the law of change of the magnitudes κ_x and κ_y.

The algorithm consists in calculating the following expressions:

$$\alpha = A_1 \sin\omega_1(t-t_0) + A_2\cos\omega_1(t-t_0) + A_3\sin\omega_2(t-t_0) + A_4\cos\omega_2(t-t_0) + A_5;$$

$$\beta = B_1\sin\omega_1(t-t_0) + B_2\cos\omega_1(t-t_0) + B_3\sin\omega_2(t-t_0) + B_4\cos\omega_2(t-t_0) + B_5;$$

$$\kappa_x = D_1\sin\omega_3(t-t_0) + D_2\cos\omega_3(t-t_0) + D_3\sin\omega_2(t-t_0) + D_4\cos\omega_2(t-t_0) + D_5;$$

$$\kappa_y = F_1\sin\omega_3(t-t_0) + F_2\cos\omega_3(t-t_0) + F_3\sin\omega_2(t-t_0) + F_4\cos\omega_2(t-t_0) + F_5.$$

where t is Moscow time in seconds. /9

$$S_x = \frac{1}{\sqrt{\tan^2\alpha + \tan^2\beta + 1}};$$

$$S_y = \frac{1}{2}\,\frac{\tan\alpha - \tan\beta}{\sqrt{\tan^2\alpha + \tan^2\beta + 1}};$$

$$S_z = \frac{1}{2}\,\frac{\tan\alpha + \tan\beta}{\sqrt{\tan^2\alpha + \tan^2\beta + 1}}; \quad \bar{l} = \frac{\bar{r} \times \bar{r}_c}{|\bar{r} \times \bar{r}_c|},$$

where the vectors $\vec{\mu}$ and $\vec{\mu}_c$

$$\bar{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}; \quad \bar{r}_c = \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix}.$$

$$\bar{m} = \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix} = \bar{r}_c \times \bar{l};$$

$$\bar{l}_0 = \begin{pmatrix} l_{0x} \\ l_{0y} \\ l_{0z} \end{pmatrix} = \frac{\bar{\kappa} \times \bar{S}}{|\bar{\kappa} \times \bar{S}|};$$

$$\bar{m}_0 = \begin{pmatrix} m_{0x} \\ m_{0y} \\ m_{0z} \end{pmatrix} = \bar{S} \times \bar{l}_0;$$

$$\bar{K} = \begin{pmatrix} \kappa_x \\ \kappa_y \\ \kappa_z \end{pmatrix};$$

$$\bar{S} = \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix}$$

As a result of the afore-mentioned calculations we obtain the matrices /10

$$P = \begin{pmatrix} s_x & l_{0x} & m_{0x} \\ s_y & l_{0y} & m_{0y} \\ s_z & l_{0z} & m_{0z} \end{pmatrix}; \quad Q = \begin{pmatrix} x_c & y_c & z_c \\ l_x & l_y & l_z \\ m_x & m_y & m_z \end{pmatrix}$$

Their product $R = P \cdot Q$ is a matrix whose rows consist of elements equal to the directions of the cosines of unit vectors of the constructed coordinate system of the satellite in a geocentric, equatorial coordinate system xyz with axis x directed to the vernal equinox point.

The magnitudes A_i, B_i, D_i, F_i ($i = 1,2,3,4,5$) are three digit decimal numbers (tenths, hundredths, and thousandths, of longitude); ω_1, ω_2, ω_3 are four-digit numbers (units, tenths, hundredths, and thousands of longitude of radian/sec).

One of described algorithms will be taken for the mass calculations.